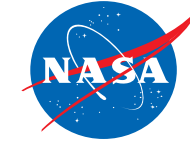


National Aeronautics and Space Administration



# Preliminary Design of the Superconducting Rotor for NASA's High-Efficiency Megawatt Motor

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# Motivation

- Reduced energy consumption, emissions, and noise of commercial transport aircraft [1]
  - Electrified aircraft propulsion (EAP) enables system-level benefits to these metrics
- EAP concepts require advances to electric machines
- NASA's High-Efficiency Megawatt Motor (HEMM) sized as generator for NASA's STARC-ABL concept



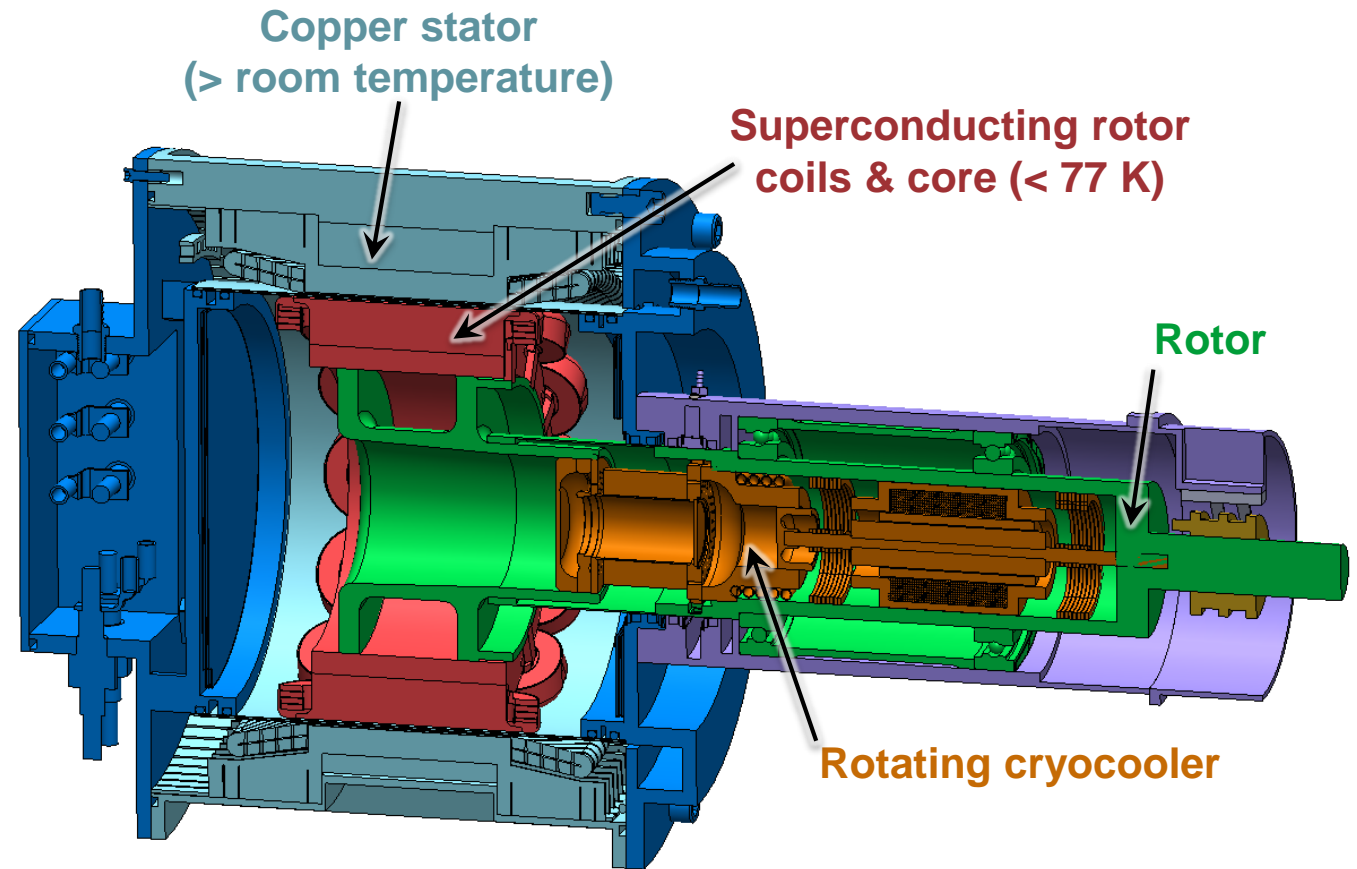
STARC-ABL

STARC-ABL		
Electric machines	Current design	With HEMM
Specific power, kW/kg	13.2	16
Efficiency, %	96	98 to 99
Performance relative to STARC-ABL rev A		With HEMM
Fuel burn, %		–1 to –2
Waste heat in generator		$\frac{1}{2}$ to $\frac{1}{4}$ (–30 to –44 kW)

# NASA's High-Efficiency Megawatt Motor (HEMM)

- Sized for generator of NASA's STARC-ABL concept
- Wound-field synchronous machine
  - Tolerant of stator fault
- Superconducting rotor
  - Negligible energy loss
  - Very strong magnetic excitation

Parameter	Value
Rated continuous power	1.4 MW
Nominal speed	6,800 rpm
Tip speed	Mach 0.31
Rated torque	2 kNm
Specific power goal	16 kW/kg
Efficiency goal	>98 %



# Outline

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## This talk

- Complete preliminary design package for rotor
  - Electromagnetic design & optimization
  - Rotor containment design & stress analysis

## Talk 2 (Scheidler & Talerico, 2018 EATS)

- Overview of current rotor design
- Fabrication & testing of sub-scale superconducting rotor coils

# Outline

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- Electromagnetic design & optimization
  - Thermal requirements
  - Optimization of rotor coil's geometry
  - Optimization of back iron geometry
- Rotor containment design & stress analysis
- Conclusions

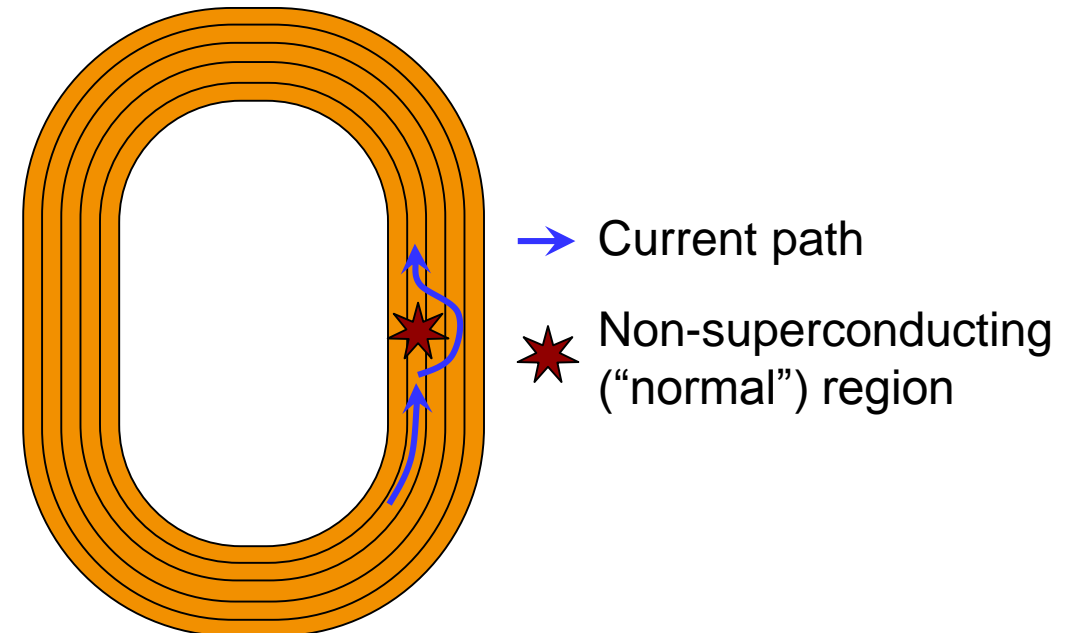
# Superconductor selection & form factor

Parameter	Value
Electrical frequency	DC
Number of poles	12
Stator configuration	Slotless
Rotor outer diameter	30 cm
Air gap	4 cm
Axial length	12.5 cm

- 2<sup>nd</sup> generation high temperature superconductor (REBCO) selected
  - Commercially available in long piece length
  - Sufficient performance at “high” temperatures in moderately strong magnetic environments

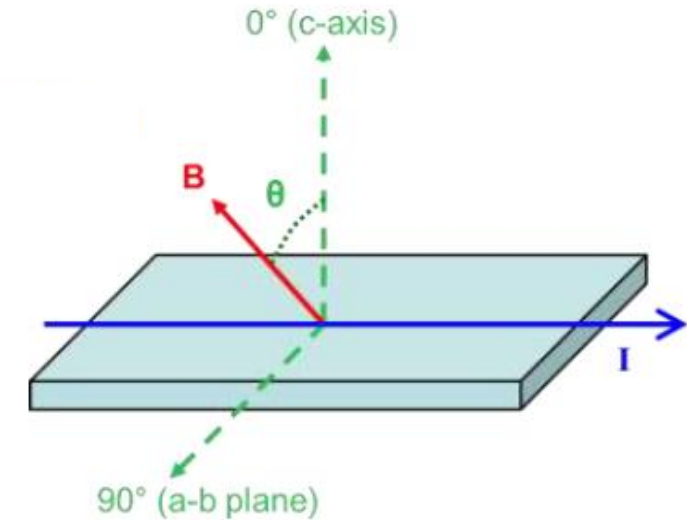
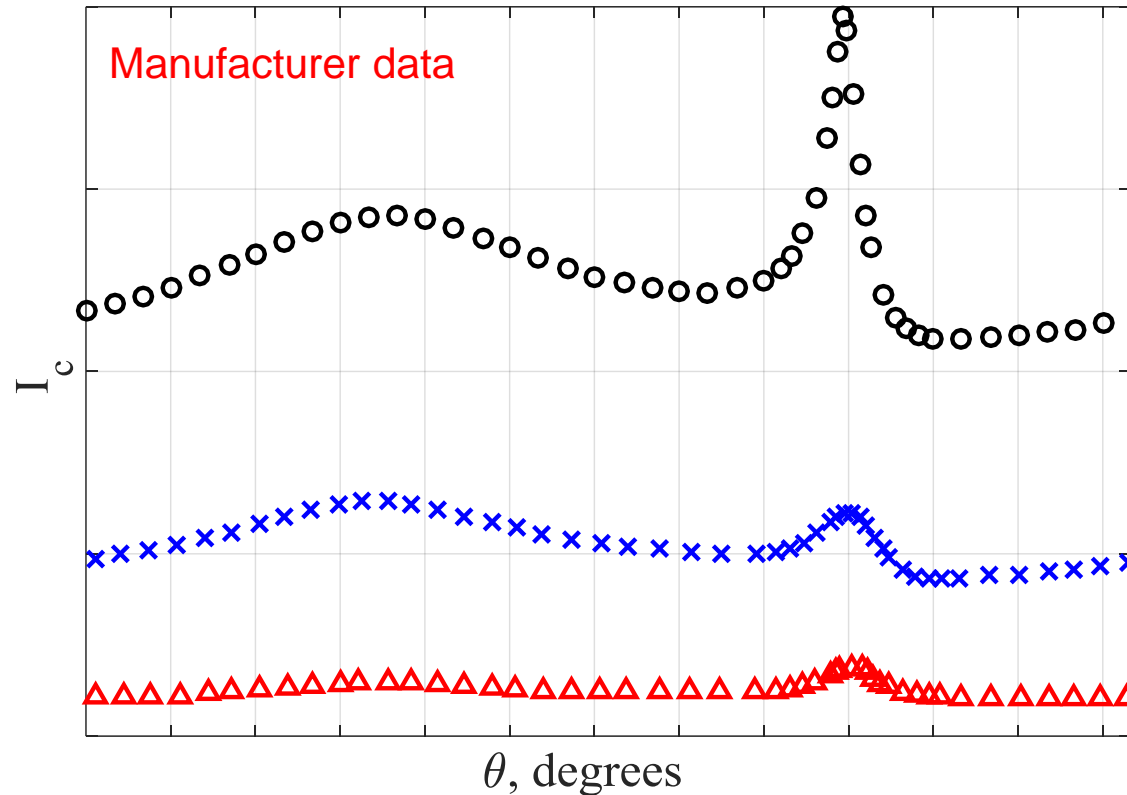
Self protection via no turn-to-turn insulation

- REBCO is a composite conductor in the form of Cu-coated thin tape
- No-insulation (NI) coils selected [9-11]
  - **Fault tolerant**
  - **Higher engineering current density**
  - Higher mechanical strength



# Superconductor current & thermal limits

- Critical current ( $I_C = I_C(T, B, \theta)$ )
  - Datasheet values  $\theta = 0^\circ$  and  $90^\circ$  are insufficient
- Datasheet specs de-rated twice: angular dependence & safety factor



## Safety factor

$\pm 20\%$  Estimate of wire variation

+  $\pm 15\%$  Modeling inaccuracy

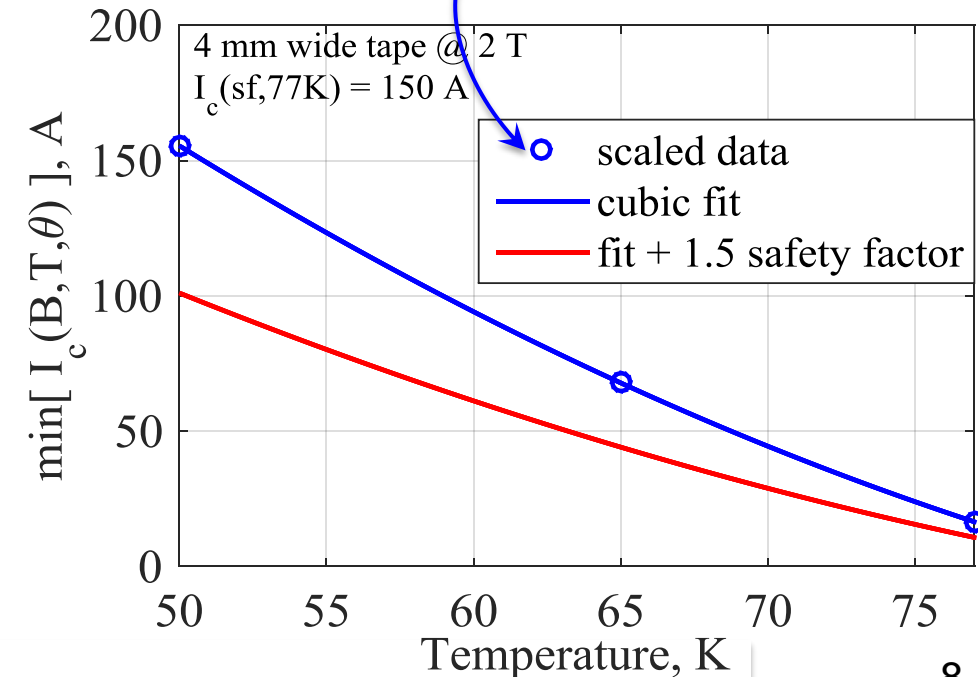
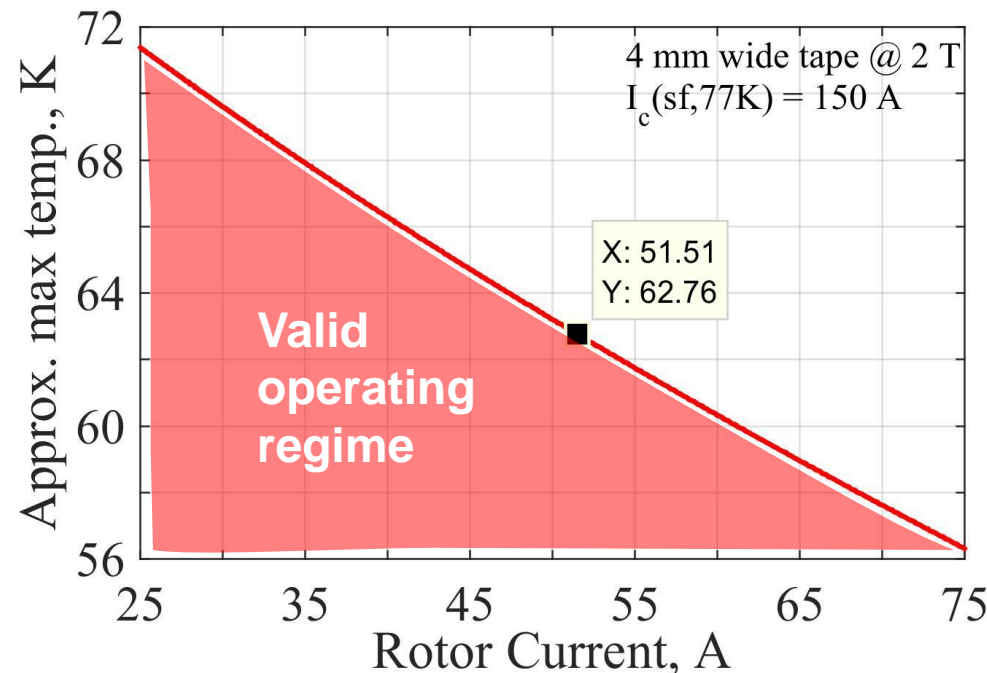
**$\pm 35\%$  ( $\approx 1.5$  safety factor)**

# Superconductor current & thermal limits

- Measurements at our operating condition obtained from manufacturer

Temperature	High performance tape (191 A @ ~0 T)		Standard tape (150 A @ ~0 T), <i>calculated</i>	
	nominal $I_c$ , A	$\min[I_c(\theta)]$ , A		$\min[I_c(\theta)]$ , A
50 K	249.4	x	lift factor →	155.0
65 K	127.1	x		67.8
77 K	28.9	x		16.5

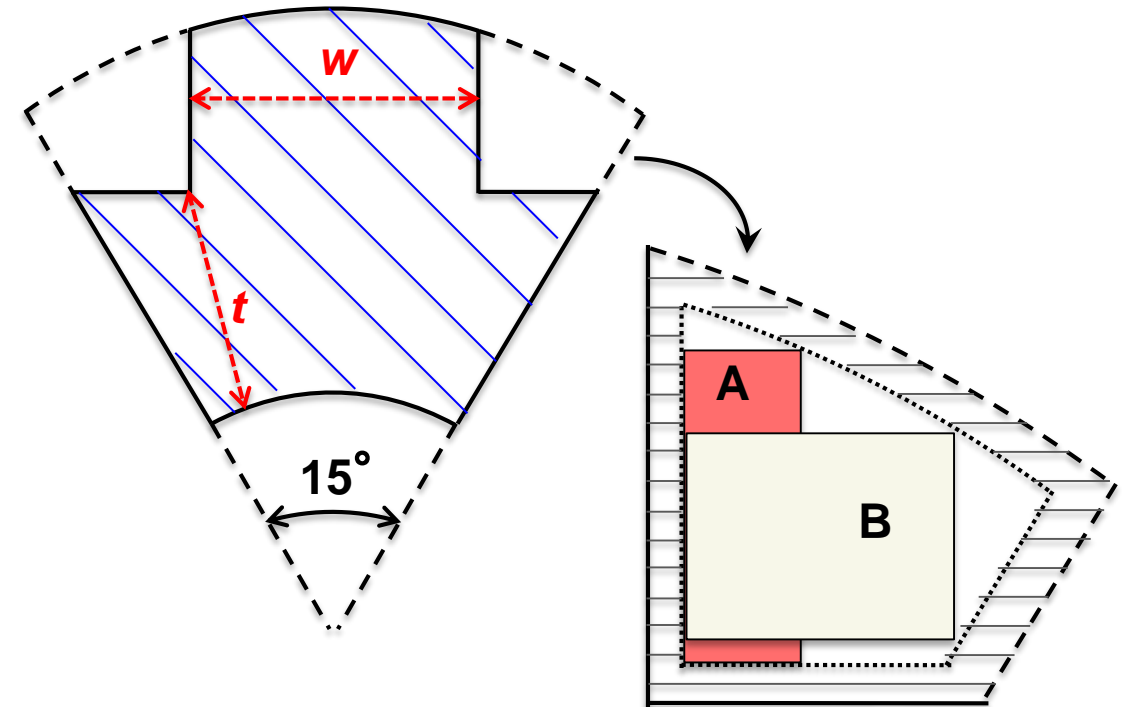
Design spec  
current 51.5 A  
temperature  $\leq 62.8$  K



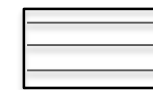


# Optimization of rotor coil's geometry

- Optimized coil's geometry for a given iron thickness & width by numerically maximizing # of turns
  - Rectangular coil cross section
  - Also outputs total length & cost of conductor, mass of iron+coil
  - 4 mm is optimal width of superconductor

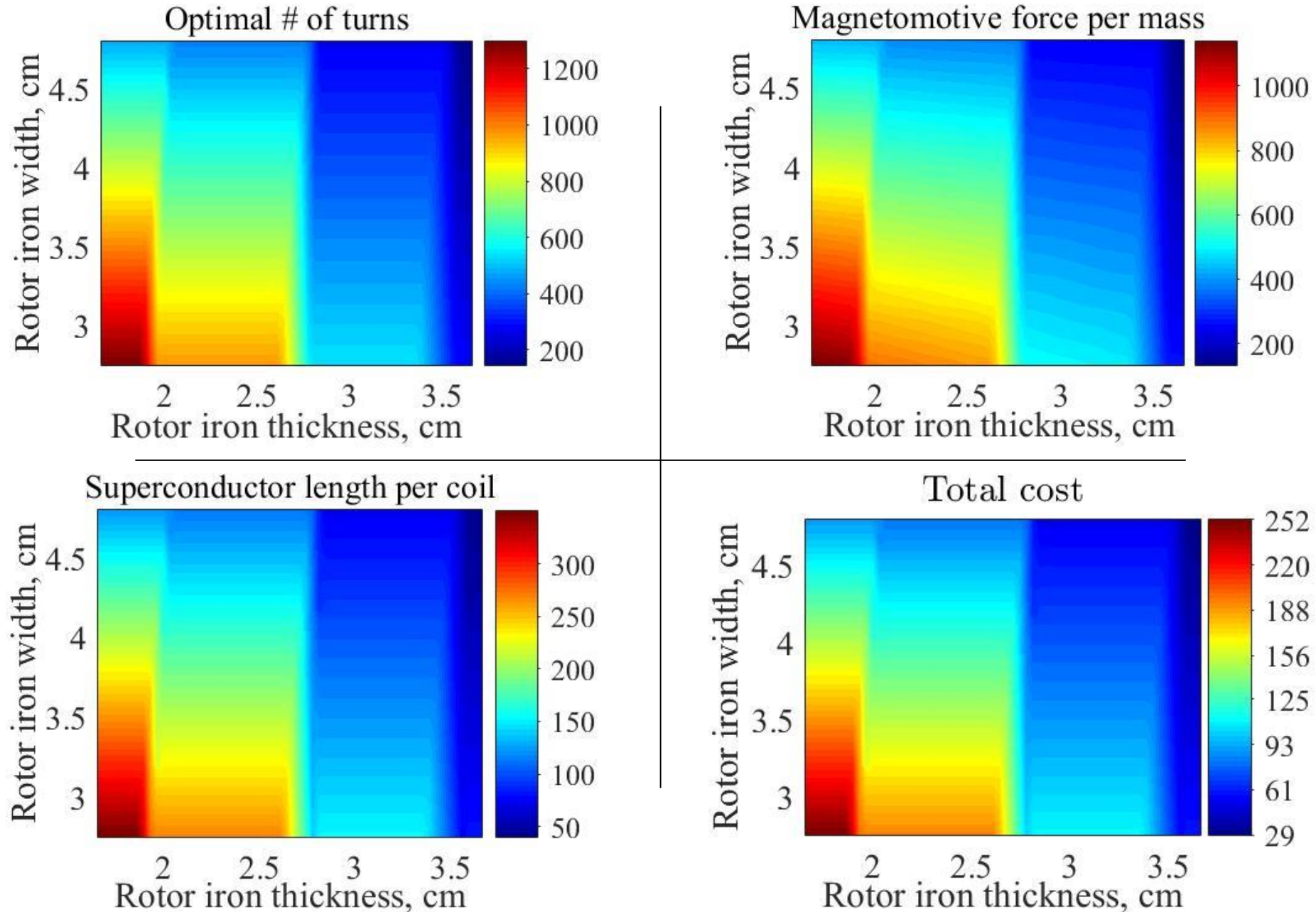


Soft magnetic material (back iron)



Region available for containment structure & clearances

# Optimization of rotor coil's geometry

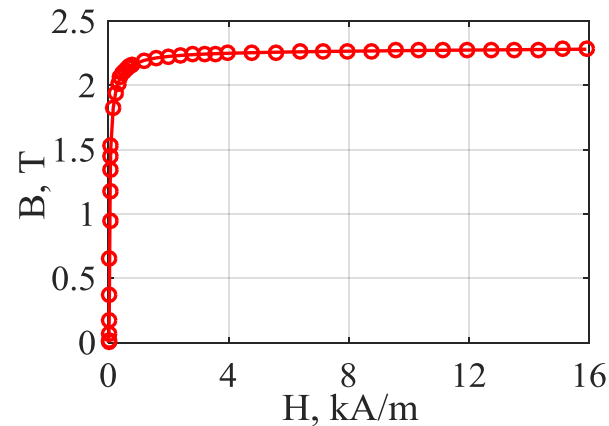


# Optimization of back iron geometry

- Custom extrapolation derived for Hipercor 50A's  $B$  vs  $H$  response
- Mesh refinement study completed
- Results consistent with 2D MotorSolve

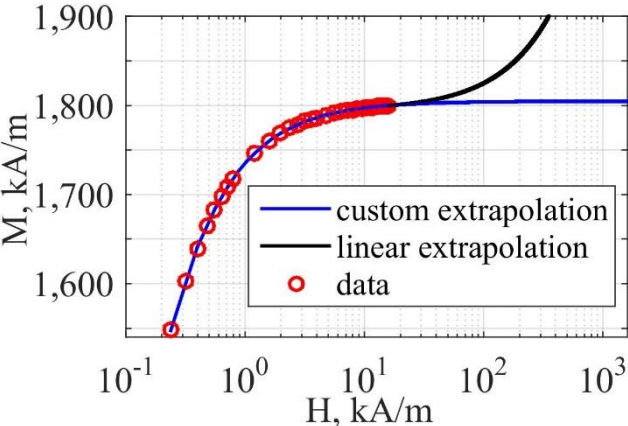
		MotorSolve	COMSOL	% difference
Current, A		75	75	-
A-Turns in coil		37500	37500	-
Avg. radial flux density	Rotor surface, T	1.999	1.9729	1.31%
	Stator surface, T	0.9028	0.8620	4.62%
Max. flux density, T		4.14	4.04	2.44%

Data from manufacturer



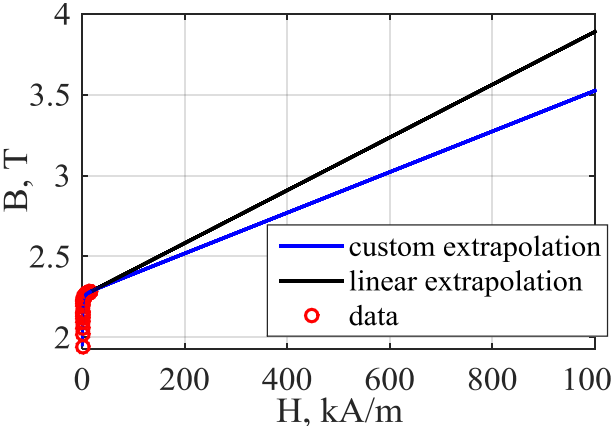
$$M = \frac{B}{\mu_0} - H$$

Curve fit, extrapolate



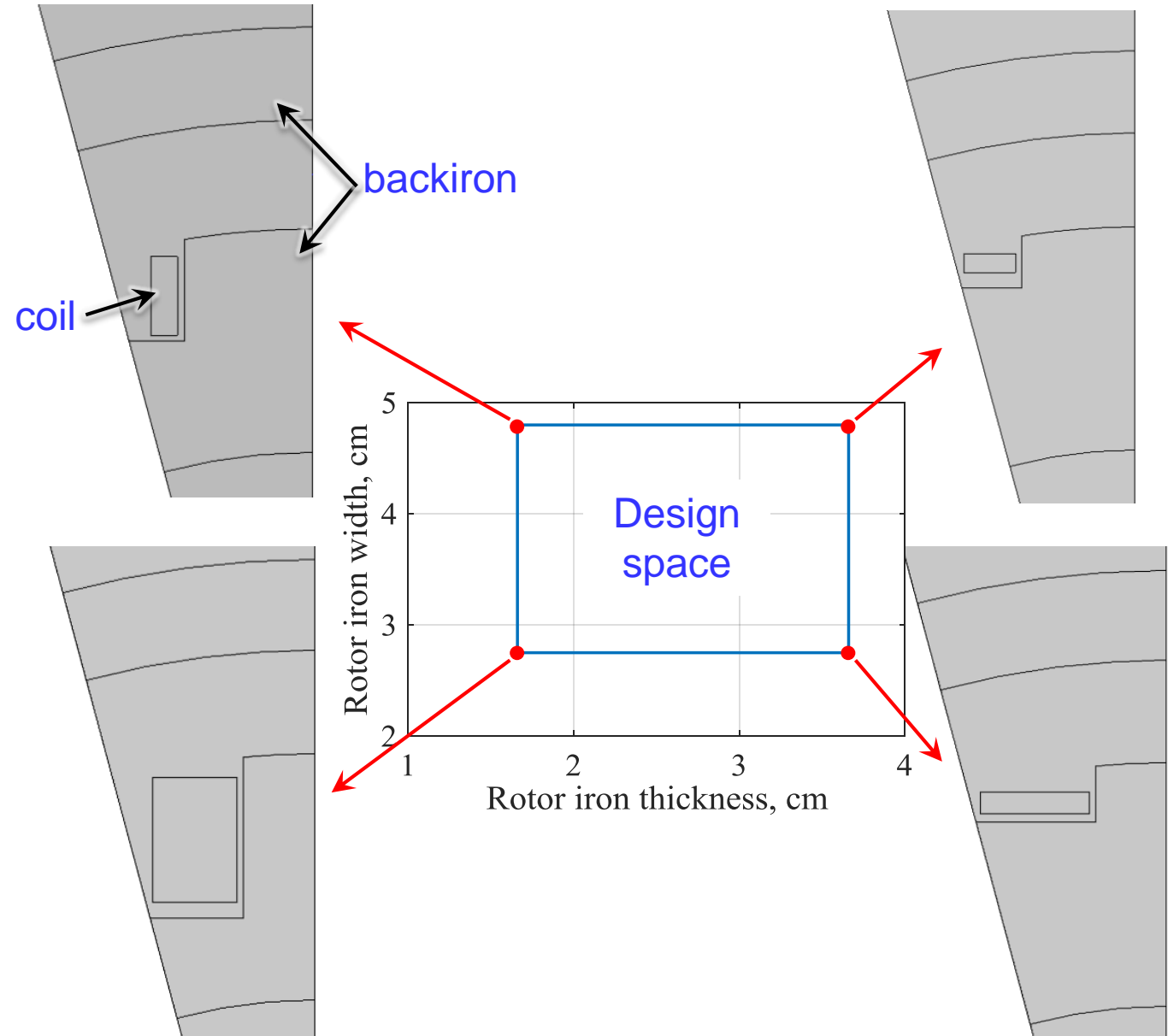
$$B = \mu_0(H + M)$$

Calculate from extrapolation



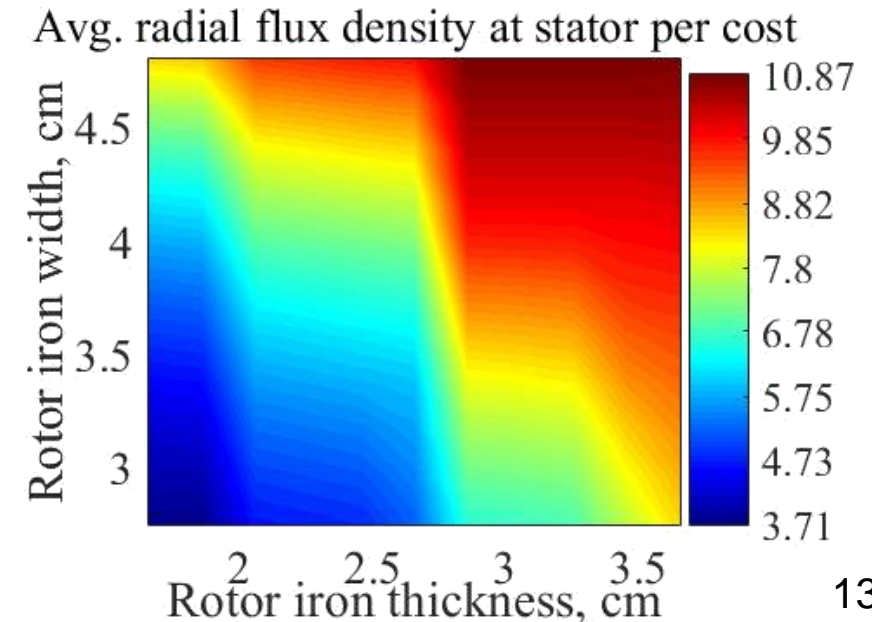
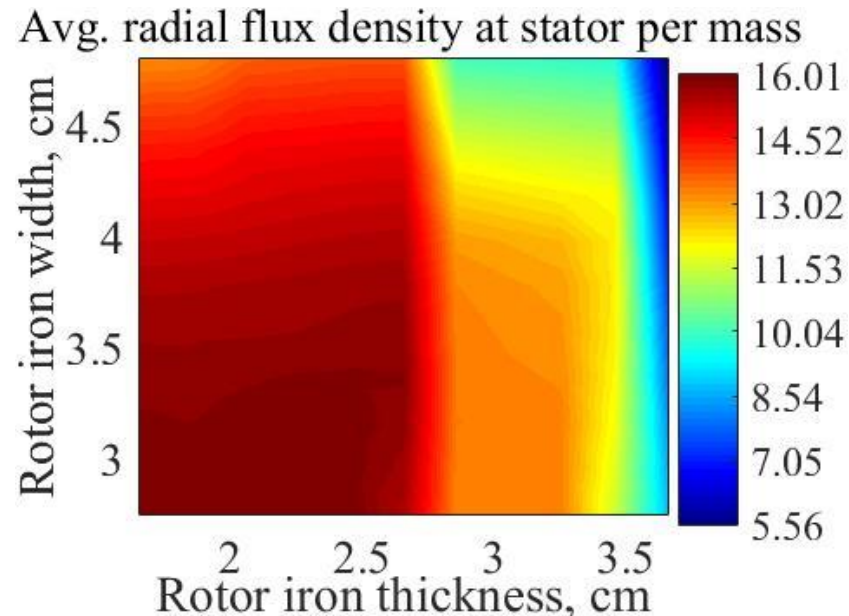
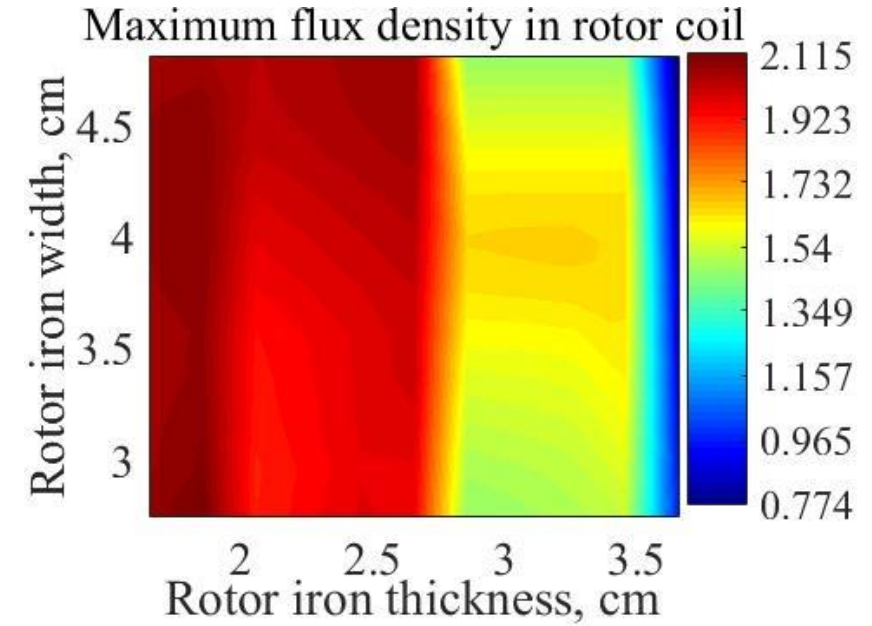
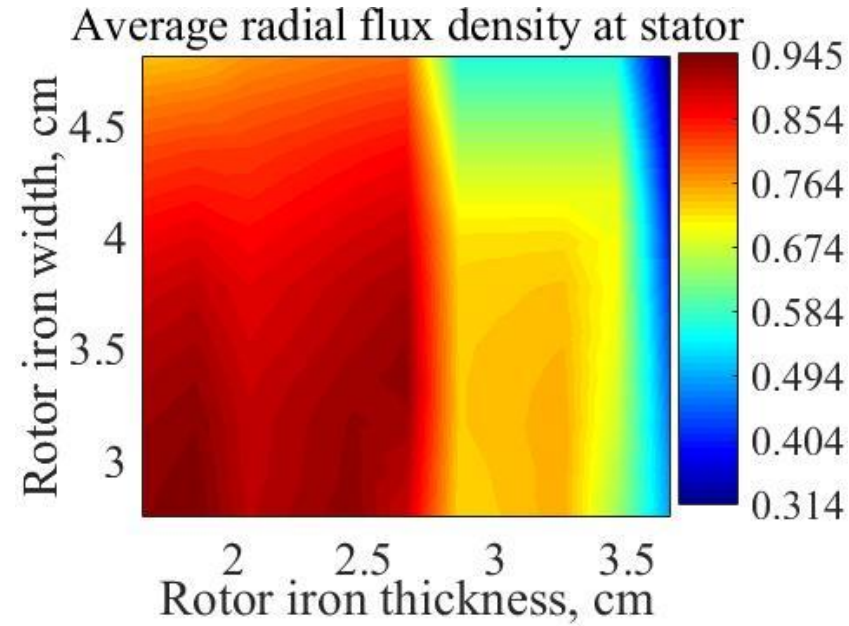
# Optimization of back iron geometry – 2D FEA

- Parametric study of iron and coil geometry
- COMSOL electromagnetic simulation
  - 2D and 3D
  - Nonlinear, static
  - No stator current



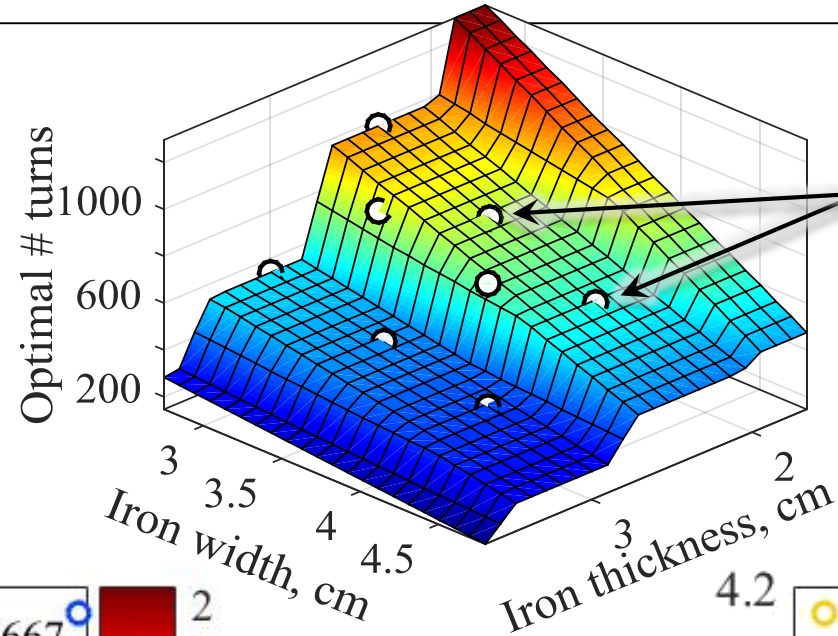
# Optimization of back iron geometry – 2D FEA

- Trends nearly mirror coil's A-turns
- Minimize rotor iron width & thickness (maximize A-Turns)
  - Diminishing returns due to magnetic saturation
- Constrained by max  $B$  in coil
- Performance & performance per mass have opposite trends than performance per cost



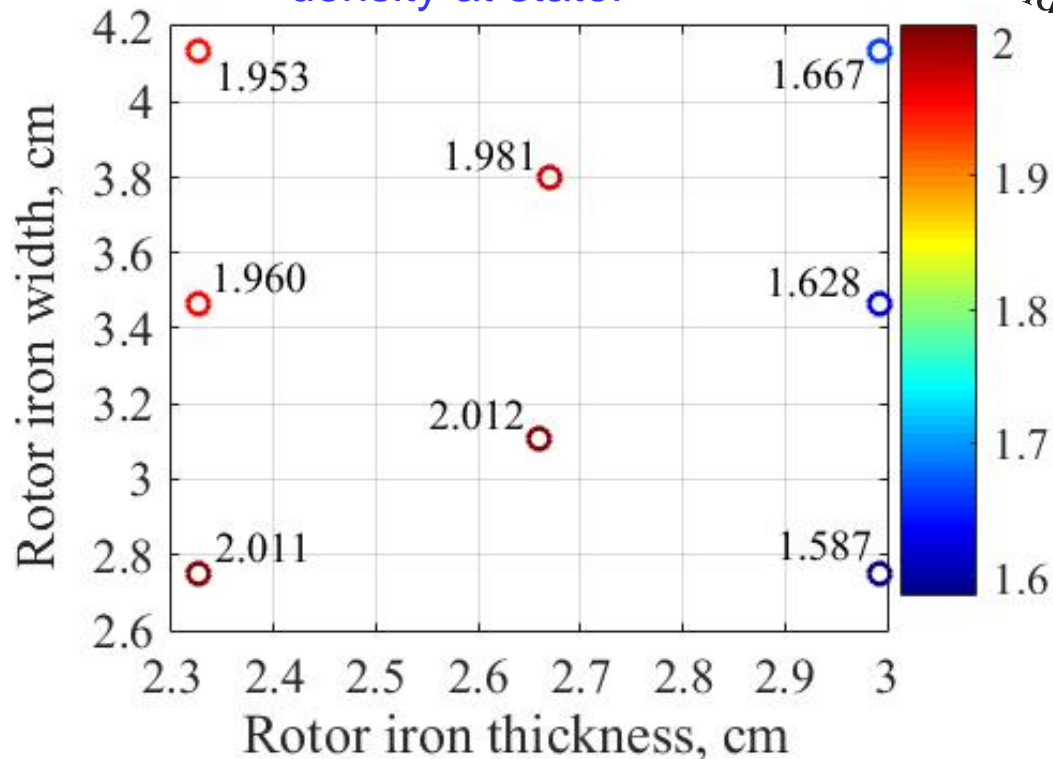


# Optimization of back iron geometry – 3D FEA

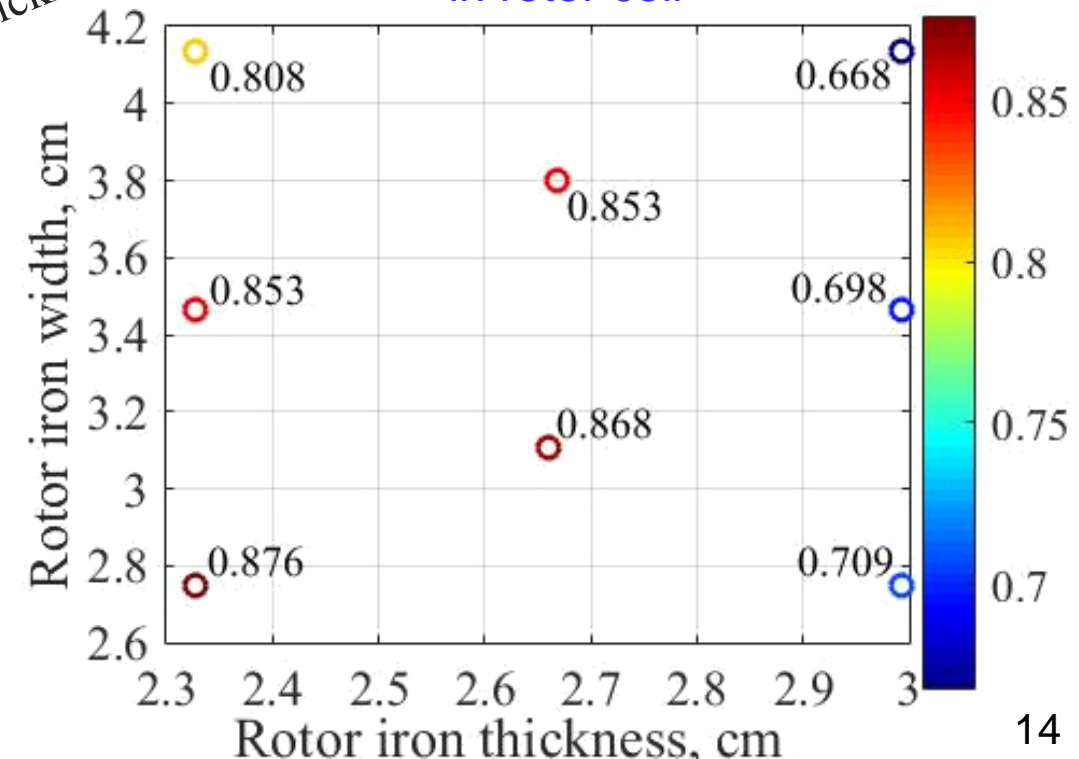


3D parametric study points

Avg. radial flux density at stator



Max. flux density in rotor coil



# Optimization of back iron geometry – 3D FEA

- Preliminary design
  - Max rotor temp. = 62.8 K
  - HTS tape = 4 mm x 65 micron
  - Rotor thickness = ~2.6 cm
  - Rotor tooth width = ~3.3 cm
- Length of HTS wire needed
  - Each coil: ~250 m
  - Total wire length: 3150 m
- Estimated total cost of HTS wire
  - **\$200K** = 3150 m \* \$60/m  
+ 5% margin

v1 design	v2 (preliminary) design	% change
75 A	51.5 A	– 31%
60 K	62.8 K	+ 5%
0.94 T @ air gap	0.96 T @ air gap	+ 2%
346 A-turns/kg	738 A-turns/kg	+ 113%
2.0 T in HTS	1.99 T in HTS	0%

# Outline

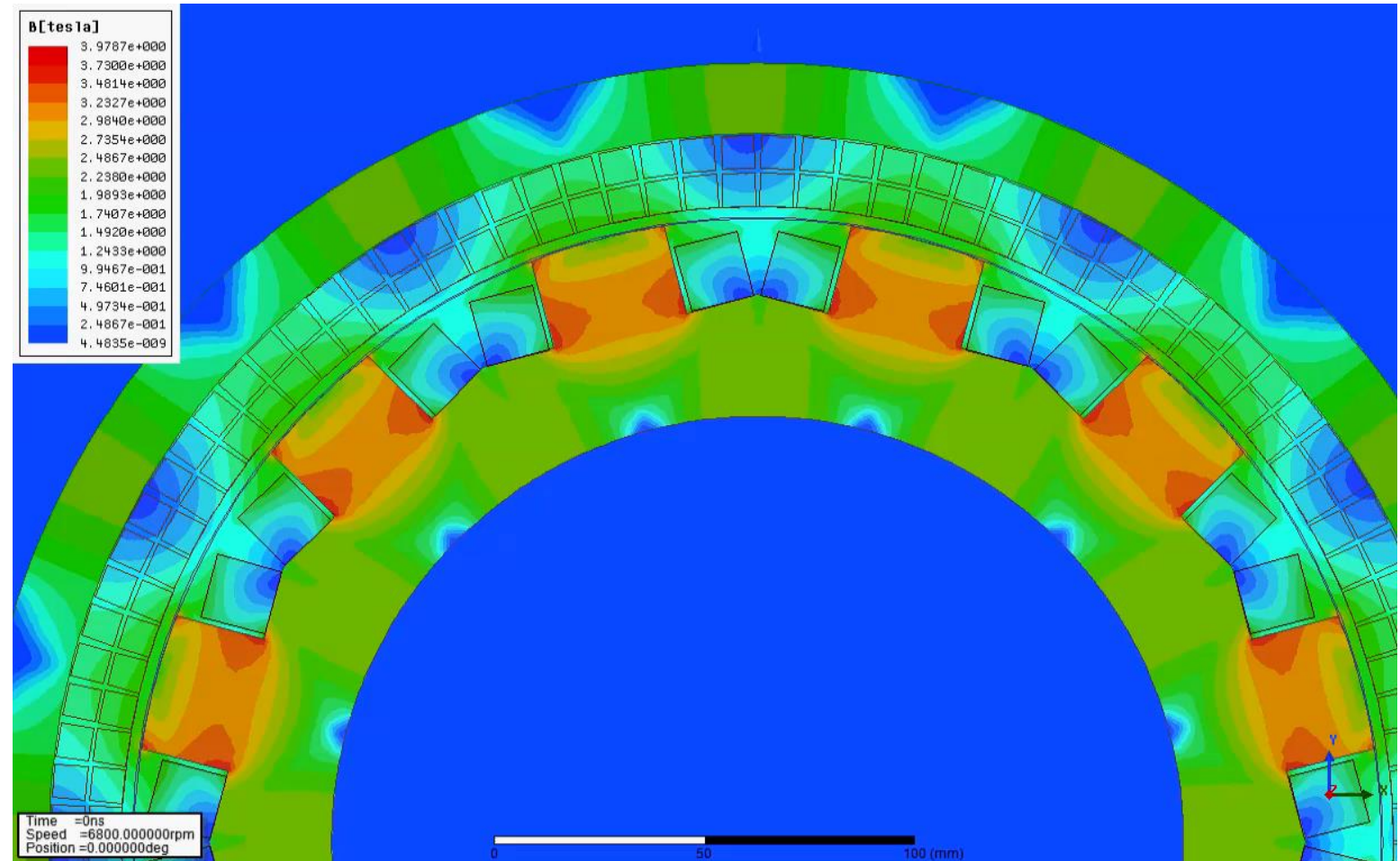
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- Electromagnetic design & optimization
  - Thermal requirements
  - Optimization of rotor coil's geometry
  - Optimization of back iron geometry
- Rotor containment design & stress analysis
- Conclusions



# Rotor containment design & stress analysis

- Only centrifugal force considered for preliminary design
  - **Neglected forces:** thermal, magnetostrictive, electromagnetic
- Rotor  $B$  variation minimal
  - magnetostriction  $< 6\text{e-}6$  m/m
  - magnetostrictive forces are negligible
- Mechanical contact modeling is critical

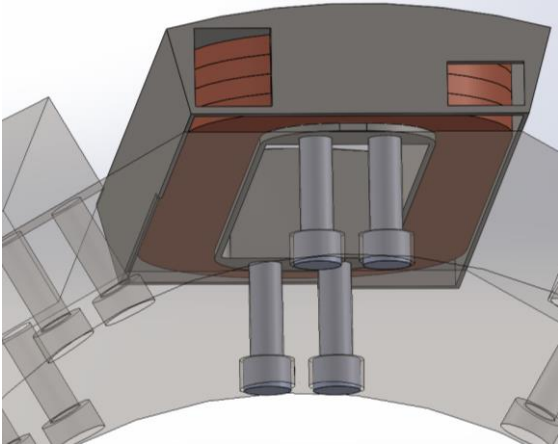


# Rotor containment design & stress analysis

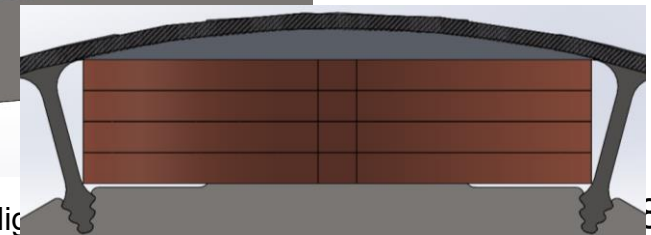
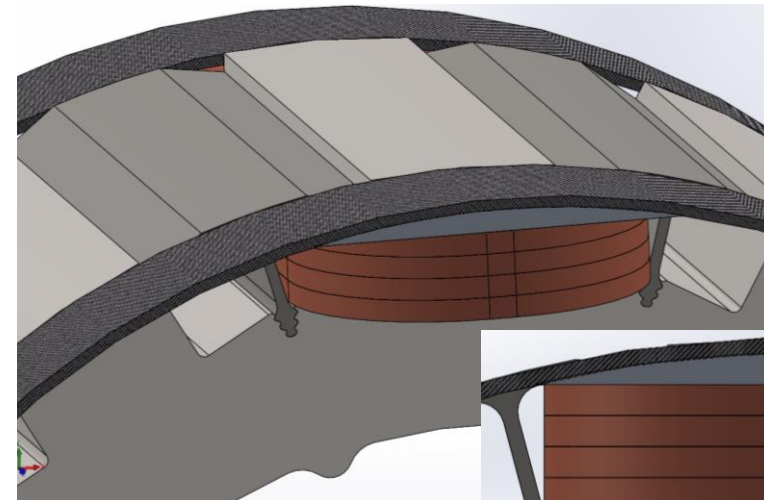
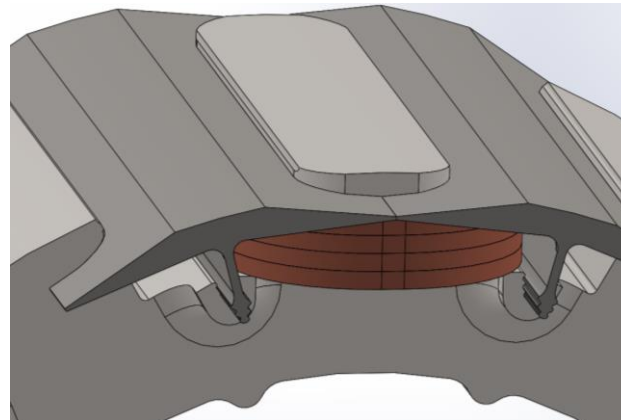
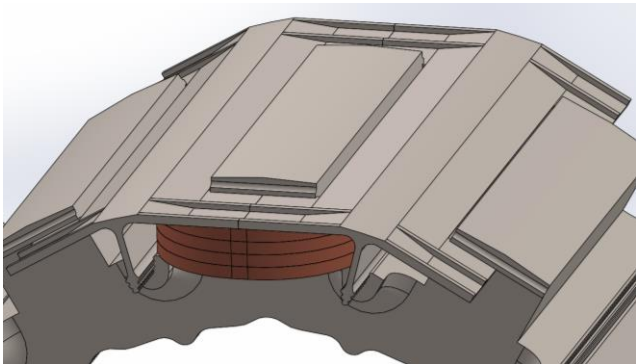
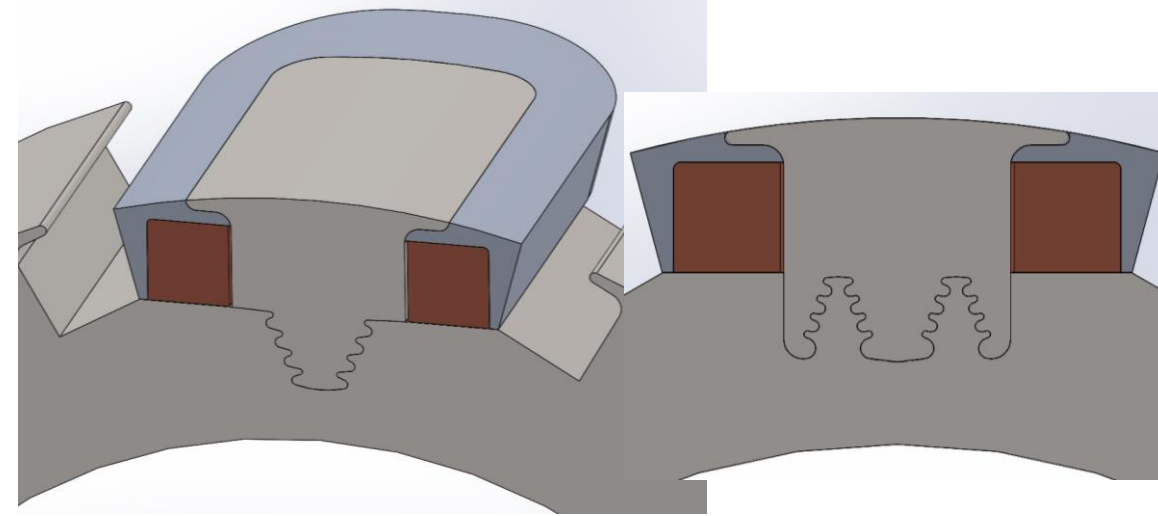
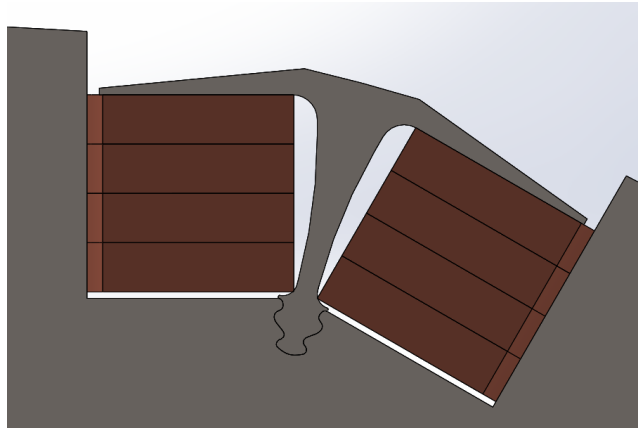
- Wide range of fixture designs considered

'fir tree' teeth

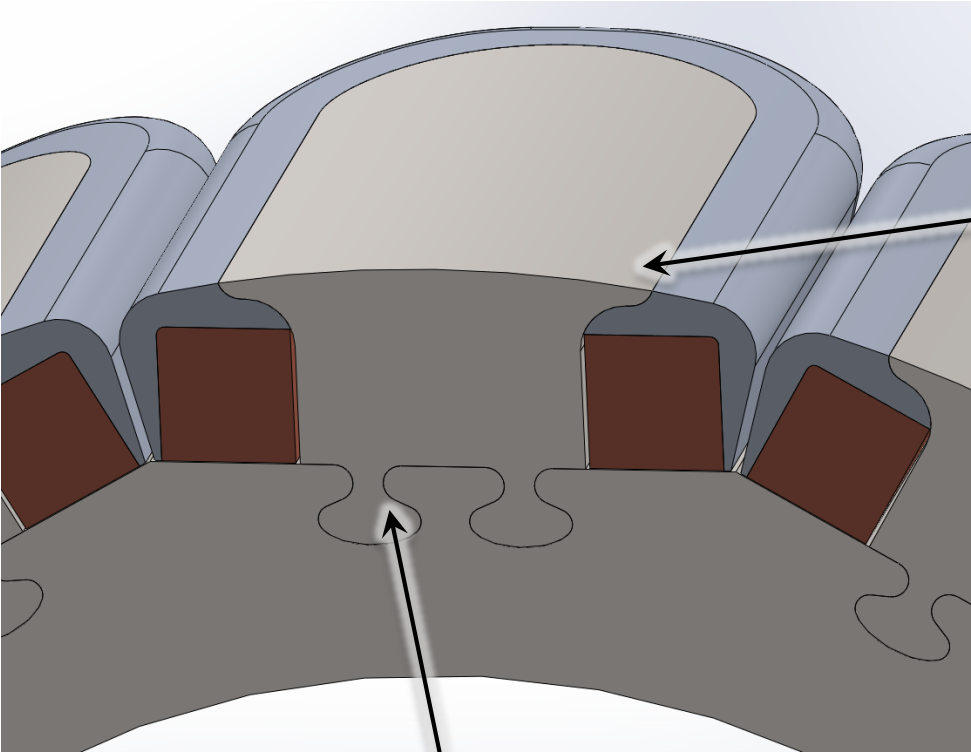
bolted fixtures



'fir tree' fixtures

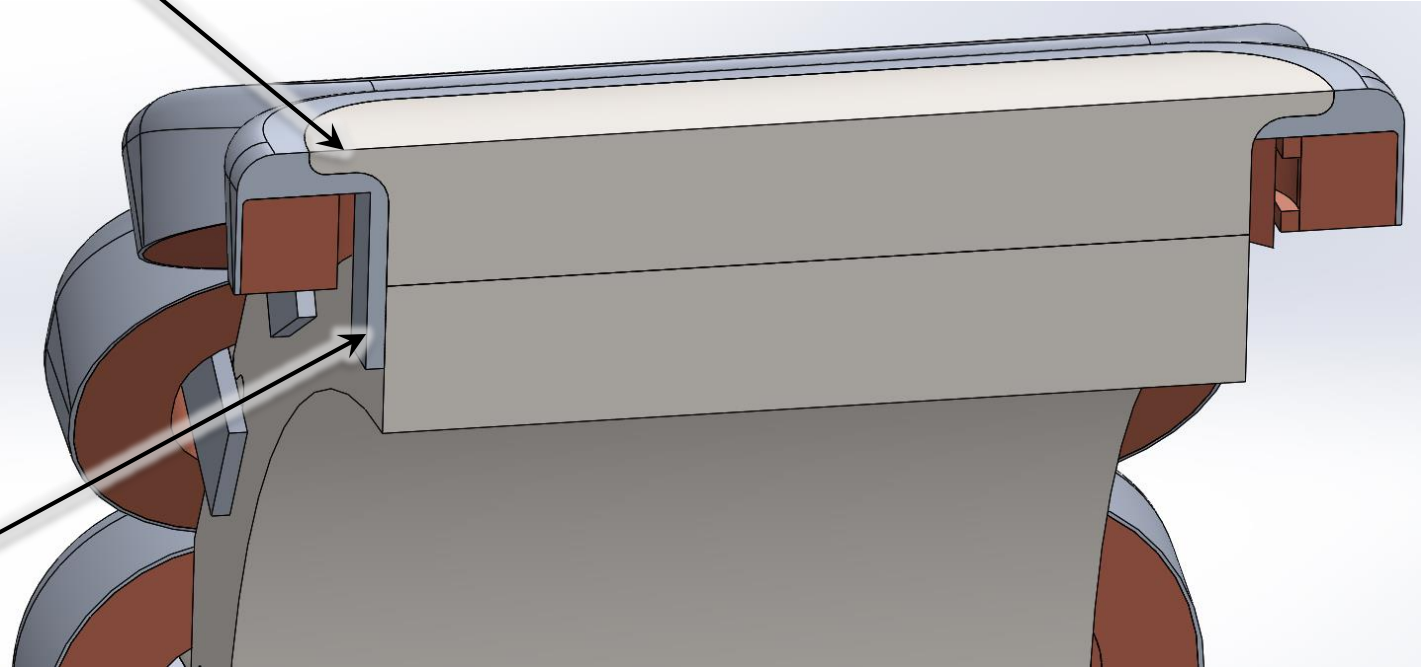


# Preliminary design – double dovetail rotor teeth



double dovetail

continuous shoulder



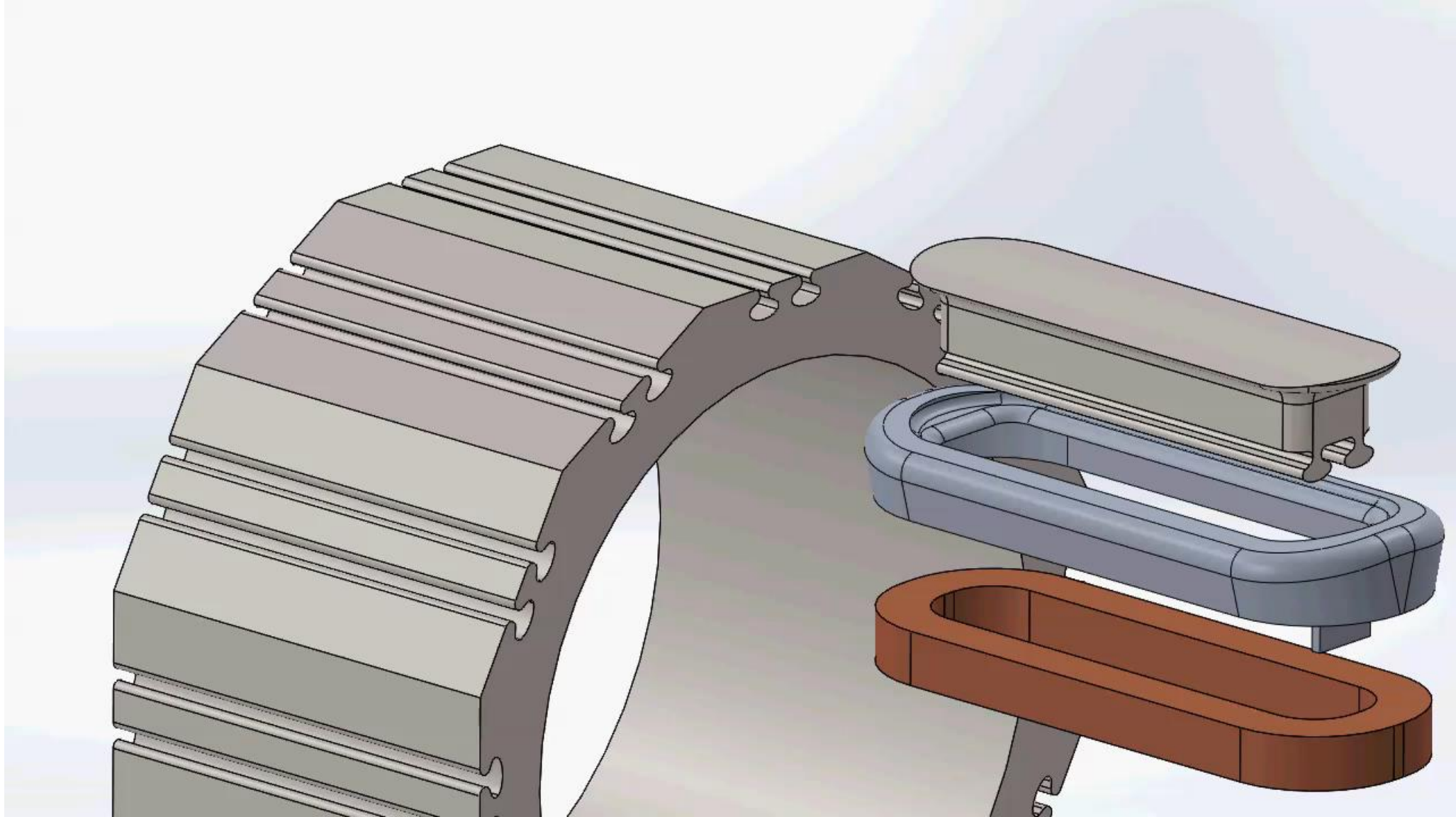
heat extraction tab

Part	Material
back iron	Hiperco 50 A
	Sialon ( $\text{SiN} + \text{Al}_2\text{O}_3$ )
Coil fixture	SiC
	SupremEx 640XA (Al 6061 + SiC powder)
	Ti-6Al-6V-2Sn



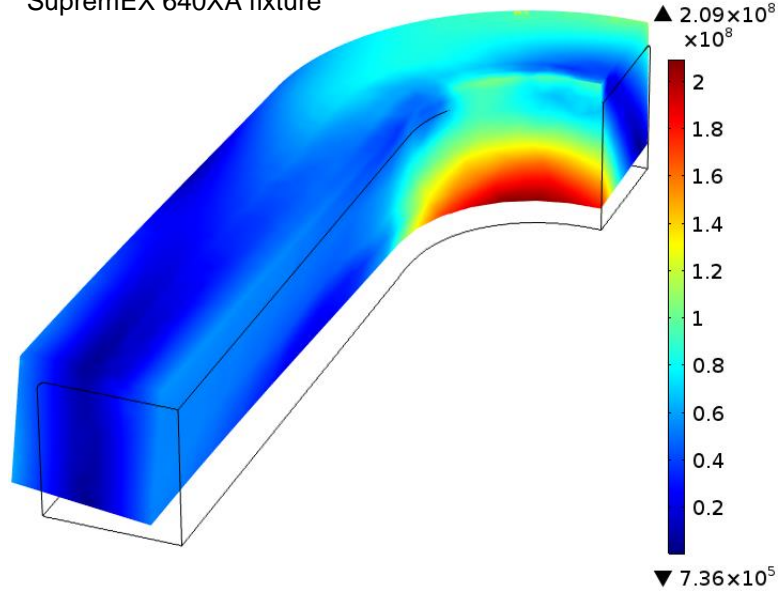
# Assembly of the rotor

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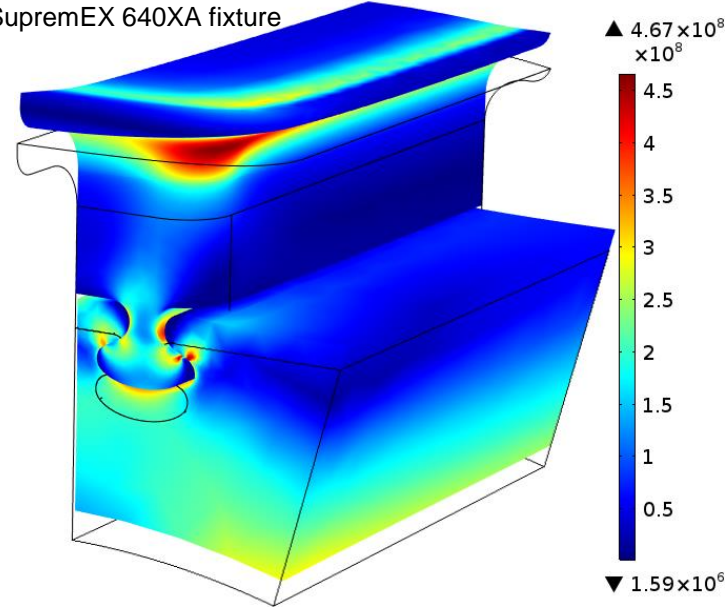


# Preliminary design – stress analysis

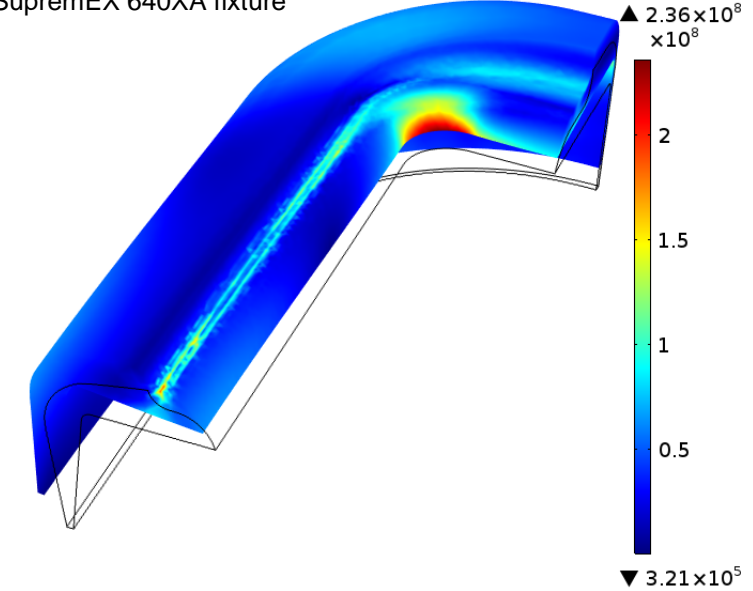
k(4)=1 Surface: von Mises stress (N/m<sup>2</sup>)  
SupremEX 640XA fixture



k(4)=1 Surface: von Mises stress (N/m<sup>2</sup>)  
SupremEX 640XA fixture



k(4)=1 Surface: von Mises stress (N/m<sup>2</sup>)  
SupremEX 640XA fixture



Fixture material	Superconductor			Hipercos 50 A			Fixture		
	'Failure' strength, MPa	Max von Mises stress, MPa	Margin	'Failure' strength, MPa	Max von Mises stress, MPa	Margin	'Failure' strength, MPa	Max von Mises stress, MPa	Margin
SiC	>550	183	2.01	694 (@ 77 K, approx.)	480	0.45	550	462	0.19
Sialon (SiN + Al <sub>2</sub> O <sub>3</sub> )		191	1.88		483	0.44	760	391	0.94
SupremEX 640XA (Al 6061 + SiC powder)		209	1.63		467	0.49	560	236	1.37
Ti-6Al-6V-2Sn		239	1.30		516	0.34	1210	338	2.58

# Outline

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- Electromagnetic design & optimization
  - Thermal requirements
  - Optimization of rotor coil's geometry
  - Optimization of back iron geometry
- Rotor containment design & stress analysis
- **Conclusions**

# Conclusions

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- Uninsulated superconducting coils offer significant benefits, but are unproven in rotor applications

## **Electromagnetic design & optimization**

- 2D FEA trends nearly mirror coil's A-turns until back iron is magnetically saturated
- Performance & performance per mass have opposite trends than performance per cost
- 3D FEA performance ~7% lower than 2D, but max flux density in coil approx. the same

## **Rotor containment design & stress analysis**

- Containment design is very challenging when pole count is relatively high & structure cannot reside in the air gap
- Double dovetail rotor teeth provide satisfactory stress margin, but may not have adequate thermal conductance

**Considerable risks remain – further analysis & sub-scale testing is needed**

# Acknowledgements

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- NASA Advanced Air Transport Technology (AATT) Project
  - Hybrid Gas-Electric Propulsion Sub-project

## References

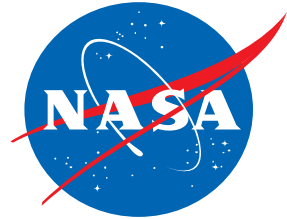
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- [1] Jansen, R., Bowman, C., Jankovsky, A., Dyson, R., and Felder, J., “Overview of NASA Electrified Aircraft Propulsion (EAP) Research for Large Subsonic Transports,” *53rd AIAA/SAE/ASEE Joint Propulsion Conference, AIAA Propulsion and Energy Forum, Atlanta, GA, AIAA 2017-4701*, 2017. doi:10.2514/6.2017-4701.
- [9] Hahn, S., Park, D. K., Bascuñán, J., and Iwasa, Y., “HTS pancake coils without turn-to-turn insulation,” *IEEE Transactions on Applied Superconductivity*, Vol. 21, No. 3, 2011, pp. 1592–1595. doi:10.1109/TASC.2010.2093492.
- [10] Song, J.-B., Hahn, S., Lécresse, T., Voccio, J., Bascuñán, J., and Iwasa, Y., “Over-current quench test and self-protecting behavior of a 7 T/78 mm multi-width no-insulation REBCO magnet at 4.2 K,” *Superconductor Science and Technology*, Vol. 28, No. 11, 2015, p. 114001. doi:10.1088/0953-2048/28/11/114001.
- [11] Hahn, S., Radcliff, K., Kim, K., Kim, S., Hu, X., Kim, K., Abrahimov, D. V., and Jaroszynski, J., “‘Defect-irrelevant’ behavior of a no-insulation pancake coil wound with REBCO tapes containing multiple defects,” *Superconductor Science and Technology*, Vol. 29, No. 10, 2016, p. 105017. doi:10.1088/0953-2048/29/10/105017.



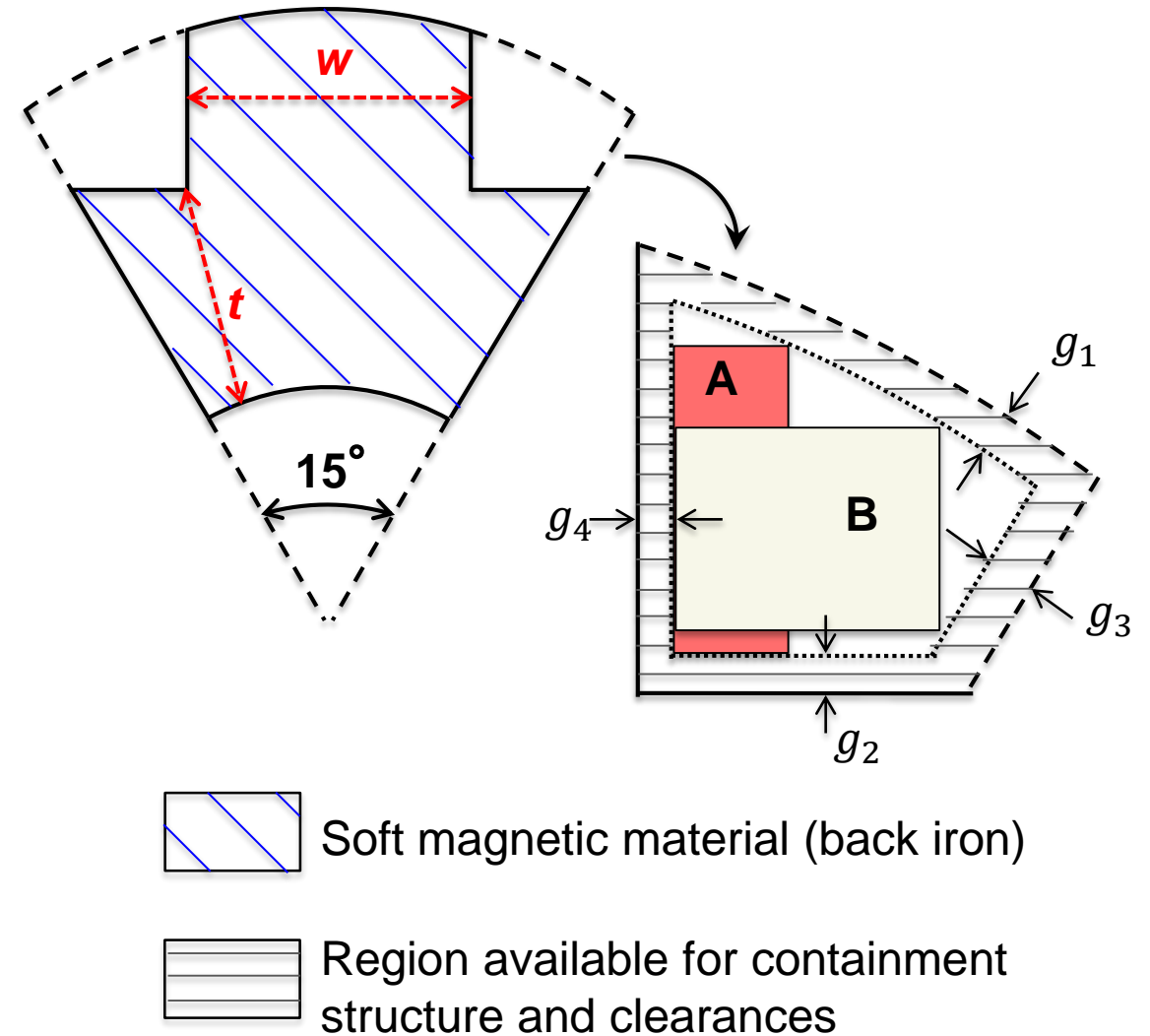
# QUESTIONS ?





# Rotor coil sizing study

Characteristic/parameter	Value
Superconductor width, mm	4
Superconductor thickness, $\mu\text{m}$	65
Min. superconductor bend radius, mm	15
Max. magnetic flux density in the superconductor, T	2
Rotor coil gap $g_1$ , mm	1.3
Rotor coil gap $g_2$ , mm	1.0
Rotor coil gap $g_3$ , mm	1.3
Rotor coil gap $g_4$ , mm	1.3



# Cryogenic yield strength of Fe<sub>49</sub>Co<sub>49</sub>

- [1] measured yield strength of Fe<sub>49</sub>Co<sub>49</sub>V<sub>2</sub> (Hiperco 50) at cryo temperatures for different grain sizes
- Yield strength increases by about 90% to 110% going from room temp to 77 K
  - Material is brittle at about 150 K and lower
- Effect of trace elements (Hiperco 50A vs 50 vs 50HS) is small [2]
- Thus, 'failure' strength for Hiperco can be increased by 90%

Material	Temp., K	'Failure' strength, MPa
Hiperco 50A after annealing	293	365
	77	694 (estimate)

1. Jordan, K. & Stoloff, N., Trans. Metal. Soc. AIME 245, p. 2027-2034, 1969.
2. Sourmail, T., Prog. Mater. Sci. 50(7), 2005. (doi: 10.1016/j.pmatsci.2005.04.001)